Enhanced Resistivity and Breakdown Strength via a Granular Two-phase Silicone Oil and Polypropylene Mixed Media Dielectric

V. Tang, S. Falabella, G. Guethlein, G. Meyer, and S. Sampayan
Lawrence Livermore National Laboratory
8000 East Ave.
Livermore, CA, 94550, USA

ABSTRACT

A new granular two-phase mixed media insulator consisting of packed polypropylene beads and silicone oil is found to have up to 10 times greater resistivity and nearly 2 times greater breakdown strength compared with the same silicone oil when operated in DC mode.

Index Terms — **Dielectric materials, oil insulation, UHV insulation, electrohydraulics.**

1 INTRODUCTION

DIELECTRIC fluids such as silicon and carbon based oils [1] are commonly used for high voltage insulation in pulsed and dc applications, such as compact accelerators, over solid insulation due to their reasonable breakdown strengths, low conductivity, self-healing properties, and allowance for disassembly. However, solid insulation can potentially provide significantly higher breakdown strengths and resistivity as they are not vulnerable to current carrying flows based on Electro-hydrodynamics (EHD) [2-3]. At the same time solid insulators lack the self-healing capability and flexibility of liquid insulators. These liquid insulation properties are important especially in experiments and devices where frequent changes, servicing, or breakdowns are likely to occur.

Here, we discuss preliminary work on a new and simple granular two-phase mixed media dielectric insulator which is designed to retain the advantages of a liquid insulator while achieving higher resistivity and breakdown strength. This is achieved by pouring and packing macro-dielectric particles into the high voltage enclosure and then flooding it with a liquid insulator such as silicone oil; the resultant mixture is theorized to slow or prevent EHD driven current carrying convective flows in pure liquid insulators for quasi-dc to dc applications. In regards to increased breakdown strength, the inclusion of macroscopic particles in the dielectric might hinder breakdown by increasing the effective flashover distance and by obstructing the flow of breakdown initialing particulates or perhaps through electron scavenging as in [4] for nanoparticle based mixtures. Our granular insulator is similar in concept to proven mix-phase insulators such as oil-impregnated paper [5-6] but has the significant additional advantage of retaining the ability of reusable liquid insulator to fill or evacuate any volume quickly in a conforming manner.

Manuscript received on 12 October 2009, in final form 29 March 2010.

We present resistivity as a function of applied electric field and breakdown measurements from experiments involving one possible two-phase insulator configuration, specifically commonly available ~3 mm diameter polypropylene beads used for injection molding [7] combined with Dow Corning 561 silicone oil fluid [8]. These two-phase resistivity and breakdown measurements are compared against experiments using only the silicone oil liquid insulator. The resistivity and breakdown values of the two-phase mixture are found to be up to ten and two times higher respectively.

2 EXPERIMENTIAL SETUP AND RESULTS

The resistivity and breakdown of the insulators were tested in a sealed ~23 cm diameter chamber housing two 4.5 cm diameter disc electrodes. The setup is schematically illustrated in Figure 1. The first or bottom electrode is connected to a negative high voltage Hiptronics Hi-pot tester which allows voltages, V_A, up to 150 kV to be applied across the electrode. The second or top electrode is grounded through a 50 MΩ resistor and connected to a high-impedance 200 MΩ op-amp in a voltage-follower configuration which measures the divided voltage and allows the effective resistance between the electrodes to be measured. From a circuit analysis viewpoint the current during steady-state is given by $V_A/(R_G+R_D)$ where R_G is the effective dielectric resistance in the gap, and R_D=40 MΩ, taking into account the finite impedance of the op-amp. The effective R_D is experimentally confirmed with an even higher impedance electrometer. Neglecting fringe field effects, the resistivity of the dielectric in the gap after the voltage is applied is thus given by $\rho_G \sim R_D A V_A / L V_D$ for $R_G >> R_D$, where A=15.9 cm^2 is the effective area of the electrode, L is the gap distance between the electrodes and typically set at 2 cm, R_G is the effective resistance of the dielectric, and V_D is the divided voltage output from the op-amp which is typically measured by a Fluke 77 hand-held meter. The applied field in the gap, E, is simply ~V_A/L. The chamber is grounded in a similar manner and equipped also with an op-amp to measure its leakage current.

Concerning the assumptions and validity of the above equation, circuit analysis which treats the Hi-pot source as a user-variable voltage source indicates that capacitive based voltages affect the measurement on a timescale greater than ~10 ms only when the applied voltage is changing. Capacitive based voltages due to changes in R_G affect the deduced ρ_G only when those changes are also on the ~10 ms timescale or less. The effective resistance of the gap, R_G, is always several orders of magnitude greater than R_D since the tested dielectrics typically have resistivities of 0.1 to ~10 TΩ-m. Thus, the diagnostic can track the effective ρ_G and changes due, for example, to charge carrying convection currents on the desired second timescale.

Mechanically, the chamber is sealed via an o-ring and the liquid portion of the insulator is continuously circulated in a closed loop in-between experiments. The pumping system continuously filters the liquid dielectric through a 15 micron mechanical filter [9] and also can continuously degas the liquid using a vacuum pump. The results discussed here, unless otherwise noted, only involve mechanical filtering of the liquid dielectric.

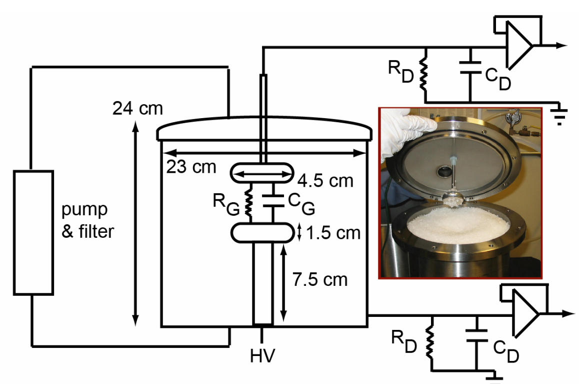


Figure 1. Experimental setup. The chamber can be filled with either pure silicone oil or the mixed media dielectric. The pump and filter are turned off during experiments. The leakage current to the adjustable top electrode is measured via high-impedance op-amp that allows the effective resistance of the dielectric in between the electrodes to be deduced. A similar setup is available for the chamber as a whole. An effective R_D of typically 40 MΩ is used, along with a C_D of ~250 pF. The inset shows the chamber filled with the polypropylene beads; additional beads are added after the chamber is sealed through a tube on the lid.

The first set of tests consists of a series of baseline measurements involving the silicone oil only. Previous data indicate that at negligible field strengths fresh silicone oil has a resistivity on the order of 1 [10] to 100 TΩ-m [8], depending on the water or dissolved gas content. Our initial tests at various applied voltages and gap distances using fresh oil indicate a resistivity of ~1-2 TΩ-m at fields of ~0.5 MV/m and a resistivity of ~0.5 TΩ-m at ~4 MV/m. These data were taken after more than a minute of dc operation and steady-state measurements. The circulation pump was turned off for this and all experiments in order to eliminate currents based on imposed flow. The first breakdown occurred at ~5 MV/m. Each time a breakdown occurs the op-amp in the detector is destroyed and replaced. This first data set is summarized by Series 1, or S1 in Figure 2. The resistivity data for this series at fields less than 2 MV/m were taken with a gap distance of 9.4 cm, while the data at 2 MV/m or greater were taken with a gap distance of 1 cm. The resistivities deduced at the lower fields are more approximate since the 1-D assumption inherent in the diagnostic model can be affected by the long gap distance. This long gap distance was only used by this Series.

The effective resistivity becomes and stays notably lower after the first breakdown even though the oil was circulated in-between runs; in addition the breakdown strength of the fluid lowered to ~4 MV/m. These data are given by S2 in Figure 2. The data were taken a minute after the voltage was applied, with the measurements reaching steady-state. Changes in applied voltage were accomplished slowly using a ~30 s period after operation of 90 s at a particular voltage. A gap distance of 2 cm was used and the voltage was scanned from 10 to 80 kV in steps of 10 kV. Multiple breakdowns did not change the effective resistivity significantly after the first one. These baseline post-breakdown experiments were repeated on multiple days and also with a gap distance of 1 cm with the same results; refilling and circulating the same oil overnight in the closed loop with the mechanical filter also did not change the measurements.

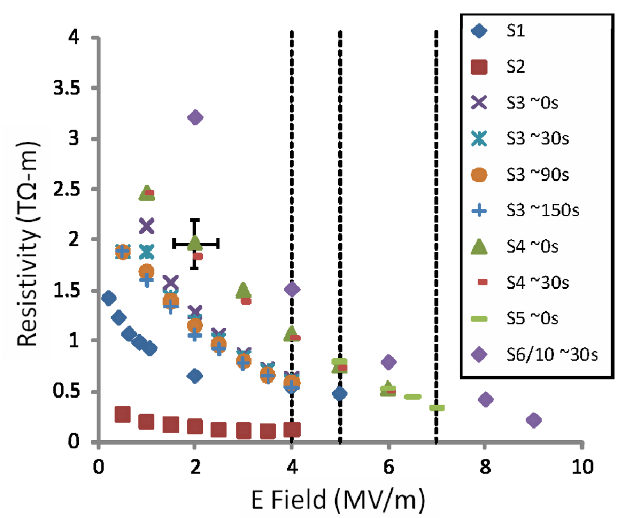


Figure 2. Measured resistivity as a function of applied field for various run Series. Typical instrument and measurement based error bars are shown for one value. The measurements for S6 have been divided by ten for clarity. The dashed bars, from left to right, indicate breakdown fields for post-breakdown silicone oil, fresh silicone oil, and the two phase granular mixture using the post-breakdown silicone oil.

With the baselines established, beads were packed into the same chamber and hence in between the electrode gap. The same oil without processing was then reinserted into the closed loop chamber. Effective resistivity data for experiments with the beads are shown as S3 on Figure 2, with measurements from ~0 s, ~30 s, ~90 s, and ~150 s after the voltage was applied using ramp periods of ~30 s and steps of 10 kV. The dwell times have deviation within +5 s/-1 s. A gap distance of 2 cm was again used and the voltage was scanned from 10 to 80 kV. No breakdown occurred. After this run, the circulation pump was turned back on for ~15 minutes and turned off again. A second run, given by S4 in Figure 2, was then performed where the voltage was scanned from 20-120 kV in steps of 20 kV applied over ~30 s with dwell time of ~30 s at each voltage. No breakdown occurred with this run either. Lastly, a third run after a similar pre-run oil circulation procedure followed. This run, designed to determine the breakdown limit of the insulator, is given by S5 in Figure 2. The voltage was scanned from 100 kV to 140 kV in steps of 10 kV applied over ~30 s with dwell times of only ~5 s at each voltage. A breakdown at 140 kV occurred, indicating breakdown field-strengths of ~7 MV/m.

The measured resistivities for the granular two-phase mixture are notably higher than for the pure silicone oil data in S1 and S2, especially for the S2 data from oil that have already experienced breakdowns or damage. Hence, the incorporation of solid beads with the "damaged" oil increased the resistivity up to an order of magnitude, and breakdown strengths by nearly a factor of two for dc operation on the order of minutes. However, for all the applied fields, the resistivity values did not reach a steady-state within the experimental timeframe for the two phase mixture as occurred in the pure silicone oil case. Figure 3 provides the transient resistivity data for several applied fields from Series 3; more work is needed to determine the final steady-state values. Additionally, the higher resistivities measured in the S4 and S5 data compared with the S3 values at the same fields appear to indicate some dependence on time and applied voltage history.

Lastly, initial experiments, given by S6 on Figure 2, where the same oil was continuously degassed with the vacuum pump in addition to being mechanically filtered resulted in significantly higher resistivities of 30 to 4 TΩ-m at field strengths of 2 to 9 MV/m respectively. A gap distance of 1 cm was used. The breakdown field threshold for this degassed mixture is to be determined.

3 DISCUSSION

Based on the experimental results so far, we believe that the granular solid-liquid two-phase mixture concept discussed above has advantages as an insulator over pure liquid or solid insulators in engineering and research applications.

Specifically, in comparison with silicone oil, the polypropylene beads-silicone oil mixture provides notably improved insulator performance. It is in addition significantly cheaper since typical prices for polypropylene beads are ~ US \$ 1k/m^3 compared with ~\$10k/m^3 for pure silicone oil. The mixture also has the advantage of a lower effective dielectric constant since polypropylene has a dielectric constant of ~2.3 [11] while silicone oil has a constant of 2.7 at room temperature [8].

One potential disadvantage of the mixture compared with the pure liquid dielectric is lowered heat-transfer ability due to minimized flow and flow paths in the system.

Compared with a solid insulator, the major advantage of the granular two-phase dielectric is that it retains some of the self-healing properties and flexibility of a liquid dielectric, while still achieving some of the higher breakdown thresholds and resistivities of a solid insulator (e.g. >1000 TΩ-m bulk resistivity for polypropylene [12]). This allows the high voltage components inside the dielectric to be serviced easily and is especially important for devices at the research and development stage which require frequent access and changes to insulated internal components. In comparison with other 2-phase dielectrics such as traditional impregnated oil-paper for HVDC cables with breakdown strengths ranging from ~30 MV/m [5] to greater than 42.5 MV/m [6] for thicknesses of 2 mm and 11.5 mm respectively, our dielectric when operated without the oil degasser exhibits lower breakdown strength of ~7 MV/m. However, the Series S6 experiments at 9 MV/m with a degassed mixture, which did not break down, suggests reasonably higher breakdown strengths than 9 MV/m since the resistivity increased by an order of magnitude compared with runs without the degasser. Operationally, we note that impregnated oil-paper insulators, like solid insulators, cannot be poured conformally into or emptied from a volume like the reusable fluid insulator or granular two-phase dielectric discussed here. We therefore see potential operational advantages with this dielectric even at lower breakdown strengths.

More extensive testing such as extended dc operation periods and additional breakdown experiments to fully quantify the self-healing abilities of these granular two-phase dielectrics are required to determine their full potential for extended high-voltage applications.

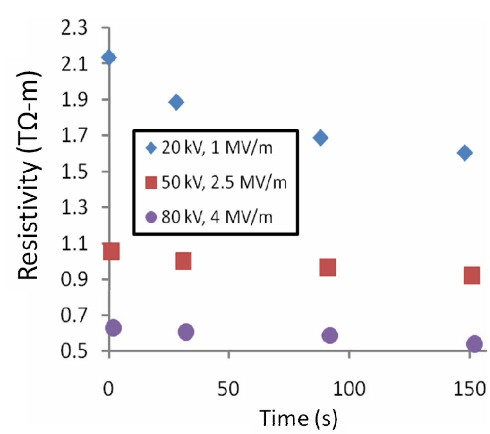


Figure 3. Some resitivities as a function of time for the two-phase mixture from S3 in Figure 2. t=0 marks the end of the voltage ramp used to apply the steady-state E fields during the experiment.

4 CONCLUSION

A granular two-phase mixed media insulator consisting of packed polypropylene beads and silicone oil is found to have notably better dielectric performance in terms of resistivity and breakdown strength compared with silicone oil alone when operated in dc mode. Resistivity values and breakdown strengths up to ten and two times greater respectively can be achieved with this mixed media concept. The mixture also has a lower cost per volume.

Because these mixed media insulator can retain the self-healing ability and flexibility of liquid insulation while providing improved high voltage performance, they could hold advantages such as reduced parasitic current losses or increased device compactness for a variety of high voltage applications. For example, these mixtures could be enabling for compact portable dc accelerators where parasitic currents must be minimized, lifetime is important, and high quasi-dc to dc gradients are required.

Overall, there is multitude of granular solid-liquid dielectric mixtures that might offer notable improvements in insulator performance compared with both pure liquid or pure solid dielectrics.

ACKNOWLEDGMENT

The authors acknowledge and thank technical assistance provided by J. Watson and E. Gower, and guidance from A. Krishnan at LLNL. We also thank J. Harris at NPS for fruitful discussions. This work was supported by the Defense Advanced Research Projects Agency under contract 1026419 and the LLNL Laboratory Directed Research and Development program with the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA2734.

REFERENCES

[1] H. G. Erdman, Electrical Insulating Oils, ASTM International, 1988.

[2] N. Felici and J.C. Lacroix, "Electroconvection in insulating liquids with special reference to uni- and bi-polar injection: A review of the research work at the CNRS Laboratory for Electrostatics, Grenoble 1969 – 1976", J. Electrostatics, Vol. 5, pp. 135-144, 1978.

[3] A. Castellanos, Electrohydrodynamics, SpringerWien, New York, 1998.

[4] J. G. Hwang, M. Zahn, F. M. O'Sullivan, L. A. A. Pettersson, O. Hjortstam, and R. Liu, "Effects of nanoparticle charging on streamer development in transformer oil-based nanofluids", J. Appl. Phys. Vol. 107, 014310, 2010.

[5] J. B. Whitehead, "The Dielectric strength and Life of Impregnated-Paper Insulation-II", AIEE Trans. Electrical Eng., Vol. 59, pp. 660-663, 1940.

[6] E. Occhini and G. Maschio, "Electrical Characteristics of Oil-Impregnated Paper as Insulation for HV DC Cables", IEEE Trans. Power App. Syst., Vol. 86, pp. 312-326, 1967.

[7] Polypropylene injection molding feed stock, Pro-fax PD702, Nat Pro-Fax PP-HF-PD702 LyondellBasell Industries, The Netherlands.

[8] Dow Corning 561 Silicone Transformer Liquid, Technical Manual, 2006.

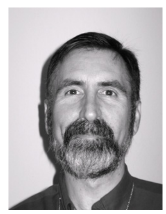
[9] Parker FA3510, Parker Filtration, Hydraulic Filter Div., Matamora, OH, USA.

[10] C.W. Wu and H. Conrad, "The temperature dependence of the conductivity of silicone oil and related electrorheology of suspensions containing zeolite particles", J. Phys. D: Appl. Phys. Vol. 31, pp. 3403-3409, 1998.

[11] E.W. Anderson and D.W. McCall, "The Dielectric Constant and Loss of Polypropylene", J. Polym. Sci, Vol. 31, Issue No. 122, pp. 241-242, 1958.

[12] R. A. Foss and W. Dannhauser, "Electrical conductivity of polypropylene", J. Appl. Polym. Sci., Vol. 7, pp.1015-1022, 2003.

Vincent Tang received the B.S. degree in chemical and nuclear engineering from UC Berkeley in 2000. He received the M.S. degree in nuclear engineering in 2002 and the Ph.D. degree in applied plasma physics in 2006 from the Massachusetts Institute of Technology. He is currently a staff researcher at Lawrence Livermore National Laboratory with research interests in compact accelerator and plasma based neutron sources as well as energetic particle physics in fusion plasmas.



Steven Falabella received the B.S. degree in nuclear engineering from the University of Lowell (now UMass-Lowell) in 1980 and the M.S. and Ph.D. degrees in applied science and engineering at UC-Davis in 1982 and 1988, respectively. His Ph.D. thesis was on RF heating of fusion plasmas. He has been employed at LLNL since 1980 and has worked on numerous projects, including magnetic-mirror fusion experiments, vacuum-arc deposition sources, RF-plasma sources, ns-scale gated x-ray pinhole cameras, high power electron linac diagnostics, novel accelerator concepts, and compact neutron sources.

Gary Guethlein was born in Long Beach, Ca. USA, in 1956. He received the A.B degree from U.C. Berkeley in 1978 and the Ph.D. degree from U.C. Berkeley in 1987. He has been employed by the Lawrence Livermore National Laboratory since 1989. His research interests include plasma physics, particle beams, and laser-plasma interactions.

Glenn Meyer is a staff member at the Center for Meso-, Micro- and Nano Technology at Lawrence Livermore National Laboratory. He has been a researcher at LLNL since 1989, working on numerous advanced technologies. His research interests range from microsensors, microsystems, photonics, applied nanotechnology, experimental physics and advanced material processing. Glenn received his MS in Ceramic Science from Pennsylvania State University and a BS in Ceramic Engineering at Alfred University.